How is Climate Downscaling Data Produced? Sausage Making Meeting

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Collaborative Climate Workshop Series:
Intermediate Activities

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The structure of our talk...

F. Dominguez: Introduction and overview of statistical downscaling results

C. Castro: Overview of dynamical downscaling and current projects.

F. Dominguez, H. Chang, B. Ciancarelli: Dynamical Downscaling results and initial analyses
Our goal is to downscale climate model data to an appropriate resolution for hydrological applications.

1. We rely on General Circulation Models (GCMs) to estimate future climate variables.

2. These projections are downscaled using either statistical or dynamical methods.

3. Downscaled atmospheric fields force the VIC hydrologic model.

4. The outcomes will be used to generate water management data for drought planning, scenarios, modeling, agricultural, tribal activities, etc.
There are basically two approaches to downscale coupled climate model projections:

- Statistical Downscaling
- Dynamical Downscaling
There are basically two approaches to downscale coupled climate model projections:

**Statistical Downscaling**

These methods assume a relationship between large-scale atmospheric variables (predictors) and local climate variables (predictands).

- **Pro**: Cheap and computationally efficient.
- **Pro**: Can use many different scenarios, model runs.
- **Pro**: Easily transferable to other regions.
- **Con**: Requires long and reliable observation data.
- **Con**: Depends on choice of predictors.
- **Con**: Assumes stationarity of predictor-predictand relationship.
- **Con**: Cannot account for feedbacks.

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**Statistical Downscaling**

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Perturbation methods are probably the simplest you can use.

\[ T_{HR\_MEAN}(m) + T_{ANOM\_PROJ}(m, e) = T_{UP\_PROJ}(m, e) \]

LLNL-Reclamation-SCU downscaled climate projections derived from the WCRP's CMIP3 multimodel dataset, stored and served at the LLNL Green Data Oasis is done using this technique (bias corrected).
Statistically Downscaled
WCRP CMIP3 Climate Projections

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Oct 31, 2008: Due to an unusually heavy demand in custom data requests over the last few days, requests may take several days to process. We are looking into adding an email notification feature to inform users of potential wait times.

Announcements (updated January 8, 2008)

Summary
This archive contains high-resolution translations of 122 contemporary climate projections over the contiguous United States. The original projections are from the World Climate Research Programme’s Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset, which was referenced in the Intergovernmental Panel on Climate Change Fourth Assessment Report. The “About” section on this website contains development information on these downscaled projection datasets (i.e. background, data attributes, and methodology).

Purpose
The archive was developed to provide planning analysts access to climate projections “downscaled” to a finer spatial resolution. Such access permits development of decision-support information and associated regional and local adaptive strategies under potential climate change. Several types of analyses are supported by this archive, including:

- regionally distributed assessments of projection frequency (Figure 1).
- location-specific assessments of projection frequency (Figure 2).
- climate change impacts assessments for social and natural systems.
- risk-based exploration of planning and policy responses.

Terms of Use
These data are being distributed to interested users for consideration in research and planning applications. Such applications may include any project carried out by an individual or organized by a university, a scientific institute, public agency, or private sector entity for research or planning purposes. Any decision to use these data is at the interested user’s discretion and subject to the Disclaimer provided below.

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Acknowledgements and Citation of these Data

Whenever you publish research based on data from this archive, please include the following acknowledgement of the superceeding CMIP3 effort: “We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP’s Working Group on Coupled Modeling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.”

In first making reference to the data from this archive, please first reference the CMIP3 dataset by including the phrase “the World Climate Research Programme’s (WCRPs) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset”. Subsequent references within the same publication might refer to the CMIP3 data with terms such as “CMIP3 data”, “the CMIP3 multi-model dataset”, “the CMIP3 archive”, or the “CMIP3 dataset”. Subsequently, please reference this archive by including the phrase “LLNL-RECLAMATION-SCU downscaling climate projections derived from the WCRPs CMIP3 multi-model dataset, stored and served at the LLNL Green Data Oasis.”

AKA: “Reclamation Data”

Statistical Downscaling
UofA developed a statistical method that accounts for climate oscillations.

When compared to the Reclamation method, it yielded similar results, both forcing and VIC output.

We decided to use the Reclamation data, because of the availability of different models/scenarios.
It is important to clarify that the Reclamation Data is Bias Corrected, so the observed climatological mean is matched in the historical data.

Raw GCM climatology for the three selected models (1950-2000)  "Reclamation" statistically downscaled climatology (1950-2000)
We ranked the IPCC-AR4 models based on their similarity with historical data and convergence in the future - for the Southwest Region.

The ukmo-hadcm3, mpi-echem5 and ncar-ccsm3 ranked highest among all models (Gleckler et al. 2008 found ukmo and mpi among the best as well).
In summary, we use the “Reclamation” statistical downscaling to force VIC. This data is bias corrected.

We use data from three selected GCMs: the ukmo_hadcm3, ncar_ccsm3 and mpi_echam5 and three emission scenarios.
The three selected models all show increase in temperature and different trends in precip.

Statistical Downscaling

Rajagopal et al. 2010
All model runs show a decrease in cool season streamflow.
Slow flow (called Baseflow in VIC) decreases, while ET depends on precipitation changes.

Rajagopal et al. 2010

Statistical Downscaling
In summary, both the Salt and Verde show a future decrease in streamflow.
The second downscaling approach is dynamical downscaling.

**Dynamical Downscaling**

- **Pro**: Produces responses based on physically consistent processes.
- **Pro**: Captures feedbacks.
- **Pro**: Can model changes that have never been observed in historical record.
- **Pro**: Useful where topographic controls are important.

- **Con**: Requires significant computational power.
- **Con**: Limited amounts of models / runs / timescales.
- **Con**: Dependant on GCM boundary forcing.
- **Con**: Problems with drifting of large-scale climate.
Dynamical Downscaling

**Definition:** Use some kind of numerical model to generate finer-resolution information from coarser resolution information. For the atmosphere, this is a limited area model.

Implicit assumption: A finer resolution and/or improved model physics (parameterizations) gives a “better” representation of weather and climate than the driving coarser resolution model (i.e. GCM).

“Better” may = more fidelity with observations and/or improved representation of physical processes

If this is not satisfied, you’re wasting money in terms of computer time to generate simulations and labor to analyze the results!!
Use the regional model as a “magnifying lens” to create higher resolution data…

Regional Climate Model (WRF)

GCM data

Historical (Reanalysis)
Seasonal Forecast (CFS)
Future Projections (IPCC)

Physically based - Regional Scale

Dynamical Downscaling
Dynamic core

Conservation Equations: Mass, motion, energy, water

Precipitation processes
Radiation
Land surface energy balance
Boundary layer

Turbulent diffusion

Boundary conditions

Green: Parameterized processes, cannot be resolved on the grid.

Dynamical Downscaling
Regional Model Grid (35km grid spacing)
GCM not only provides lateral boundary conditions. It is also used to force the interior of the model...

This helps maintain the appropriate variability in model fields at upper levels and at large scales.
WRF-simulated precipitation with and without interior forcing

June 1993: Central US flood
We are performing different types of Dynamical Downscaling at the UofA using WRF:

- **Historical (Reanalysis)**
  - Time Period: 1979-2000
  - Status: Done this spring

- **Seasonal Forecast (CFS)**
  - Time Period: 1982-2000
  - Status: Done Aug. 09

- **Three IPCC AR4 models for A2 emission scenario**
  - Time Period: 1968-2081
  - Status: One model done as of this April
Science Question: How will climate in the Southwestern United States change due to global warming?

Methodology: We use WRF with spectral nudging to downscale 113 (1968-2081) years of SRES A2 data from three “well performing” IPCC models.
We chose to downscale the **three well performing IPCC AR4 models** that best represent the historical precipitation and temperature climatology in the Southwest and upper atmosphere circulation patterns in the Northern Hemisphere. **These also have different GCM precipitation projections for Arizona (i.e. include “wet” and “dry” models)**

HadCM3: Completely done

MPI Echam: GCM data being obtained

CCSM: Will get these data soon

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Dominguez et al (2009)
While statistically downscaled data will generally give us two variables (P and T), dynamical downscaling gives us approx. 90. At a 6hry resolution.

Winds (different levels), temperature, humidity, ET, potET, SWE, snow depth, soil moisture ...

Dynamical Downscaling
RCM variables being provided to the hydrologic modeling team

2m Surface air temperature
10 m Surface winds
Relative and absolute humidity
Precipitation
Short and longwave radiation
Snow water equivalent
Snow depth

Higher confidence
Variables more dependent on dynamic core

Dynamical Downscaling

Lower confidence
Variables more dependent on model parameterizations
Required resources for UA
dynamical downscaling activities

**Salaries**

Faculty (Castro, Dominguez), a postdoctoral researcher, graduate students, technical support
$100-200 K per year when fringe benefits included.

**Computing equipment**

Multiprocessor linux clusters, RAID storage systems (10s of terrabytes), local desktops, data interface?
$100-200 K for linux clusters (already covered through faculty startups, federal grants), $10-30 K for RAID systems, $5 K for workstations

**Travel and publications**

$5-10 K per year

Current partner funding from this project is contributing to funding highlighted items

Dynamical Downscaling
Dynamical Downscaling IPCC data
The process of downscaling the UKMO-HadCM3 data involved several steps:

- **Feb 09**
  - Select the models to downscale consulting with stakeholders
  - Obtain data at all 6-hrly temporal resolution and all the variables.
  - Process the data to input into the regional climate model
  - Modify the RCM for these types of simulations.
  - “Nurse” the model run.

Using 128 processors

Dynamical Downscaling
Preliminary analysis of results...

1968-2000 June July and August precipitation climatology of WRF downscaled UKMO-HadCM3 data show a much more realistic spatial representation of the North American Monsoon than the raw model.
Preliminary analysis of results...

1968-2000 monthly climatology shows that WRF represents the timing and intensity of the Monsoon more realistically than the raw model.
Preliminary results of future precipitation show that the 2001-2040 climatology has a generalized higher precipitation – Particularly in July, as compared to the 1968-2000 monthly climatology.
We believe the reason for these changes in precipitation can be summarized as follows (Salt-Verde Basin).

In the winter, dominated by large scale circulation, the raw GCM (UKMO) shows an increase in precipitation.

In addition to the winter increase, the RCM more realistically captures the summer rains (wet bias). The increase in global atmospheric moisture might be driving an increase in summer rain. This must be investigated.
To contrast with statistical downscaling

The statistical downscaling inherits the change in precipitation from the GCM and assigns a historical climatology. Consequently, it doesn’t show any difference in the summer.
When comparing Dynamical Downscaling Results with (Bias Corrected) Statistical Downscaling, we see a wet bias in summer precipitation, and considerable variability in winter precipitation.

The hydrologic modeling team will speak about how they are dealing with the bias.
We have talked about the climatological analysis, now let’s look at the interannual variability…
Connections between seasonal precipitation variability and large scale teleconnections

Equatorial Pacific sea surface temperature anomalies (ENSO + PDO) → Change in large-scale atmospheric circulation patterns over Northern Hemisphere → Impact of large-scale teleconnection on regional precipitation pattern

Precipitation interannual variability (statistical analysis (SPI, EOF)) → Coherent seasonal response in Southwest US precipitation

Sea Surface Temperature

Regression maps of SST, 500mb Geopotential Height based on dominant precipitation pattern
Statistical analysis methods:

**Precipitation normalization**

  – Standard Precipitation Index (SPI): Accounts for non-normal distribution of precipitation

**Spatial pattern recognition**

  – Rotated Empirical Orthogonal Function Analysis (REOF)

**Relationship of dominant modes of precipitation variability to large-scale forcing factors**

  – Regression Analysis between precipitation modes and SST, geopotential height
What we look for to assess natural variability in downscaled climate data

**GCM:** need to capture the **SST forcing and associated large-scale circulation pattern**

- **RCM:** need to capture the regional **precipitation variability**

- Expectations for dynamically downscaled output:
  - Capture **Pacific forced interannual variability**, which must be seen in the dominant regional precipitation patterns, associated sea surface temperatures and large scale circulation
Dominant pattern of variability for winter season
Typical winter precipitation anomaly during El Nino year

Source: Climate Prediction Center
Model

Observation

Correlated SST forcing

Dominant winter precipitation pattern (SPI)
Wet southwest US, Dry northwest US

Positive PNA pattern

Correlated geopotential height teleconnection

Positive ENSO pattern
Early summer teleconnection patterns
(late June, early July)

(Castro et al., 2001)
Well known anticorrelation between precipitation in central U.S. and southwest U.S.

Quasi-geostationary Rossby wave

Correlated geopotential

Correlated SST forcing
RCM with dynamically downscaled GCM data is able to capture:

- Seasonal precipitation variability (winter and summer)
- Large-scale forcing corresponds to the dominant precipitation pattern
  - ENSO pattern
  - Stationary patterns in the atmospheric circulation both in winter and summer
    - Quasi-geostationary Rossby wave (different driving mechanisms for winter and summer)

The regional model is adding substantial value to the representation of the interannual variability of the driving global model.
Conclusions

1. The Reclamation statistically downscaled data has been used as atmospheric forcing for the VIC model.

2. All three selected models show a decrease in streamflow and slowflow and variable precipitation and ET in the Salt/Verde.

3. Dynamical Downscaling of HadCM3 data has been finalized.

4. Climatological analyses show clear improvements when compared to raw GCM data.
Conclusions

5. In the dynamically downscaled WRF HADCM3 interannual variability is well captured for both summer and winter seasons.
Lessons Learned:

1. Obtaining the forcing data is NOT trivial, in this case we are fortunate that the NARCCAP effort is underway.

2. Probably most of the personnel time was spent modifying the data to be input into WRF. However, “nursing” the model also involves personnel time.

3. Pre-processing must be done in advance of model runs.

4. Forcing data is not perfect, some days have garbage.

5. We are still dealing with the issues of data sharing. These involve SIGNIFICANT volumes of data transfer.

6. We anticipate storage needs on the order of 100 TB for future simulations.
Model Observation

Dominant winter precipitation pattern

Correlated geopotential height teleconnection

Correlated SST forcing